Uncertainty ranges in estimating e_0 and low-density consolidation characteristics for polymer treatment assessments

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Abstract

Estimation of e_0 is an important parameter when gaining information on the behaviour of tailings after polymer treatment, as it is a critical input when trying to predict field scale consolidation behaviour with the use of modelling techniques. Many laboratory experiments were undertaken to determine the uncertainty ranges in estimated values of e_0, varying both the starting height of the tailings, starting solids concentration, with and without polymer treatment in beakers, graduated cylinders and custom built 10 L columns with evenly spaced sample ports. 95% confidence intervals range from 0.047~0.14 for e_0 values in the range of 3.5~4.5 highlighting the robustness of the experimental methods and the viability of using experimentally determined e_0 as an input for consolidation modelling.

Sample ageing and solids concentration were found to have an impact on compressibility and permeability behaviour of the suspensions, however it is likely that the variability relates to an increased polymer demand rather than variation of the consolidation behaviour of the material itself. Observations made using varying starting height of the tailings suggest that this factor has no impact on void ratio, however increasing the internal diameter of the vessels used to measure the void ratio at varying effective stress suggests that wall effects may be a factor for slurries with high solids densities.

1   Introduction

The use of polymer addition to increase dewatering and subsequent rate of consolidation of tailings in Tailings Storage Facilities (TSF's) has been a subject of many recent papers and commercial applications. To assess the potential benefits from polymer treatment, it is useful to carry out laboratory evaluations including consolidation testing, followed by numerical large-strain consolidation modelling. This allows the implications of the variations seen in laboratory testing to be assessed under a variety of conditions relevant to expected site deposition rates and rates of rise.

While the above methods outlined to assess the benefits of polymer treatment have undergone incremental development, many challenges remain. Some of these are summarized as follows:

(1)   Settlement tests, combined with most laboratory consolidation systems, do not generally provide high quality data for material loaded under effective stresses of 0 to 5 kPa-however this region of

effective stress is of particular importance for high rate of rise scenarios involving material that consolidates slowly.

(2) Historically, most laboratory tests are carried out on samples that may have aged in the time between their generation and subsequent testing in an off-site laboratory. This ageing process has been observed to vary the outcome of testing for some materials.

(3) More advanced laboratory equipment, such as the Seepage-Induced Consolidation Test (SICT) are relatively limited in availability, particularly in the context of on-site testing carried out at mine sites to attempt to avoid ageing effects.

(4) There is insufficient data available to make firm conclusions as to the experimental variability of some of the parameters required from testing. Therefore, small differences seen between polymer treated and untreated samples could, in some cases, be partially a result of inherent test variability. Indeed, some SICT programs have indicated significant variability would have a meaningful effect on the resulting consolidation model inputs (Estepho, 2011).

To provide insight into some of these issues, a laboratory test program was carried out wherein large number of settlement tests were carried out on "fresh" and "aged" materials, from a sample prepared at different initial solids concentration, using three different settlement vessels. This work was carried out using an identical slurry, derived from laboratory-standard soils mixed in fixed ratios.

2   Experimental program

2.1   Slurry preparation

A synthetic tailings material was used for these tests. It was developed from a mixture of laboratory silica silt, and kaolin clay, produced by Sibelco Australia Ltd Salt (NaCl) equivalent to 2 g per litre of slurry was added, to give a dissolved solids concentration approaching that of a typical tailings slurry. The dry components of the soil were blended without a sand fraction, to minimise the likely occurrence of segregation when prepared across a range of slurry solids concentrations at the following weight blends: Silt 40% and Clay 60%.

The sample was prepared at two solids concentrations, 25 and 37wt%. Where samples were treated with polymer (Polymer treated-PT), it was added to the 25wt% sample at 331 g/t and to the 37wt% sample at 852 g/t and subsequently mixed in a Hobart mixer until sufficient structure had been generated. Where polymer was not used (Untreated-UT), an equivalent volume of additional water was added to ensure a consistent volume during testing. Eight tests were carried out on each experimental run, to enable assessment of the precision of the testing procedure. Solids concentration was varied twice High Solids 37wt% (HS) and Low Solids 25wt% (LS). Samples were also prepared both as an Aged Sample (AS) and Fresh Sample (FS) using 1350 and 1020 g/t polymer respectively for the polymer treated samples (see Table 1).

Table 1   Experimental runs

Run	Solids (wt%)	Volume of Tailings Slurry (mL)	Treatment condition	Sample Age
1	25% (LS)	700	Untreated (UT)	Fresh sample (FS)
2	37% (HS)	700	Untreated (UT)	Fresh sample (FS)
2a	37% (HS)	700	Untreated (UT)	Fresh sample (FS)
2b	37% (HS)	700	Untreated (UT)	Aged sample (AS)
3	25% (LS)	1000	Untreated (UT)	Fresh sample (FS)
4	37% (HS)	1000	Untreated (UT)	Fresh sample (FS)
4a	37% (HS)	1000	Untreated (UT)	Fresh sample (FS)
4b	37% (HS)	1000	Untreated (UT)	Aged sample (AS)
5	25% (LS)	700	Polymer treated (PT)	Fresh sample (FS)
6	37% (HS)	700	Polymer treated (PT)	Fresh sample (FS)
6a	37% (HS)	700	Polymer treated (PT)	Fresh sample (FS)
6b	37% (HS)	700	Polymer treated (PT)	Aged sample (AS)
7	25% (LS)	1000	Polymer treated (PT)	Fresh sample (FS)
8	37% (HS)	1000	Polymer treated (PT)	Fresh sample (FS)
8a	37% (HS)	1000	Polymer treated (PT)	Fresh sample (FS)
8b	37% (HS)	1000	Polymer treated (PT)	Aged sample (AS)

2.2   Polymer preparation

The polymer used in this study was Rheomax® ETD9050, which is an anionic polymer of approximately 30wt% charge and has a molecular weight of 24 m/Daltons. A Rheomax® ETD9050 solution of 0.5wt%/vol concentration was prepared by weighing dry polymer into a clean and dry 200 mL glass jar. 5 mL of acetone was added to "wet" the polymer. The polymer and acetone slurry was gently mixed before 195 mL of Perth tap water (non-potable) was added. After the water was added and the bottle resealed, the polymer was shaken vigorously for at least one minute. The bottle was then transferred onto a rotating wheel and further conditioned for at least 2 hours.

2.3   Determination of void ratio at zero and varying effective stresses

1 L glass beakers were filled with slurry, at both 700 and 1000 mL volumes to measure the impact of slurry height and allowed to settle until settlement had ceased. All of the supernatant was removed by decanting supernatant until a small amount of the solids was decanted. A syringe was then used to remove ~10 mm of bed height and % solids measurement was conducted by oven drying to establish e_0.

Void Ratio at varying effective stress and hydraulic conductivity was measured by using 1 L graduated cylinders with an internal diameter of 62 mm. The cylinders were filled at both 700 and 1000 mL volumes and allowed to settle, during which time the settlement rate was recorded. After settlement had ceased, the consolidated solids were sectioned into six parts (from top to bottom) and the depth of the section from the mud line was recorded and used to calculate the effective stress.

Each sample section was placed in a pre-weighed drying tin to measure the % dry weight. This process was repeated using custom-built 10 L columns with an internal diameter of 150 mm to compare the impact of wall friction effects. The columns have evenly spaced sample ports to remove sections of consolidated sample (sequentially from top to bottom) as per the procedure used for the 1 L cylinders.

Hydraulic conductivity was estimated from the settlement tests based on the method proposed by Takada

and Mikasa (1986):

$$k = s \frac{1+e_{ini}}{G_s - 1} \tag{1}$$

Where:

s = initial settling rate (in the same units as permeability);

e_{ini} = the void ratio at the start of settling, which is distinct from sedimentation void

       ratio;

G_s = the Specific Gravity of solids;

Although this method has been adopted by a variety of researchers investigating consolidation behaviour (McDermott and King, 1998), the authors are unaware of a specific procedure for its application.

It is noted that settlement rate begins to decrease almost immediately from commencement of the test, hence initial measurements are unlikely to represent the exact rate at the start. For the purposes of this paper, the settlement rate data versus. time was plotted, and the trend extrapolated to t = 0. This intercept was taken as the initial settlement rate for estimation of the hydraulic conductivity.

2.4 Large strain consolidation testing

Testing was carried out by pouring sample into a 150 mm diameter cell, allowing it to settle, then placing filter media and weights for initial consolidation to approximately 2 kPa. Once complete, the top cap of the cell was fastened in place, and loading was carried out incrementally up to 800 kPa. Each load stage was initially applied in undrained conditions to allow excess pore pressure to equalise, the drainage ports were then opened on the top of the cell and consolidation was allowed to occur using top-drainage only. Hydraulic conductivity was inferred by means of the time to dissipation of 50% of the excess pore pressure at the base of the sample. After the final load stage to 800 kPa, the sample was unloaded in stages, disassembled, density was then calculated from dry solids and volume of the specimen.

3 Results and discussion

3.1 Determination of e_0 comparison

Consideration was given to the variability that could be present in measuring e_0, compressibility and permeability comparing aged, fresh, PT and UT samples. Observations during the testing program supported this with significant differences noted in permeability and compressibility across beaker, cylinder and column tests.

There was almost no variation in e_0 with varying slurry height. The solids concentration, however, did have an impact on the value of e_0; the high solids slurry (37wt%) displays a consistently lower e_0 than the low solids slurry (25wt%) for both the PT and the UT slurries. Such a dependence of e_0 on slurry solids concentration is consistent with other experimental data (You and Znidarcic, 1994).

Error associated with the determination of e_0 was evaluated for PT and UT at varying slurry heights and solids concentrations. The experimental data illustrated in Figure 1 shows excellent repeatability within each test condition with 95% confidence intervals from 0.047~0.14 for e_0 values in the range of 3.5~4.5 (where population size = 8).

Polymer treatment causes a small, but statistically relevant increase of the e_0 for high solids but has no impact on the e_0 for low solids slurry. It is noted that this effect may be due to the variation in polymer treatment for low vs high solids slurry (331 versus 852 g/t respectively).

Overall, the determination of e_0 using the methodology described earlier is robust, precise and fit for purpose
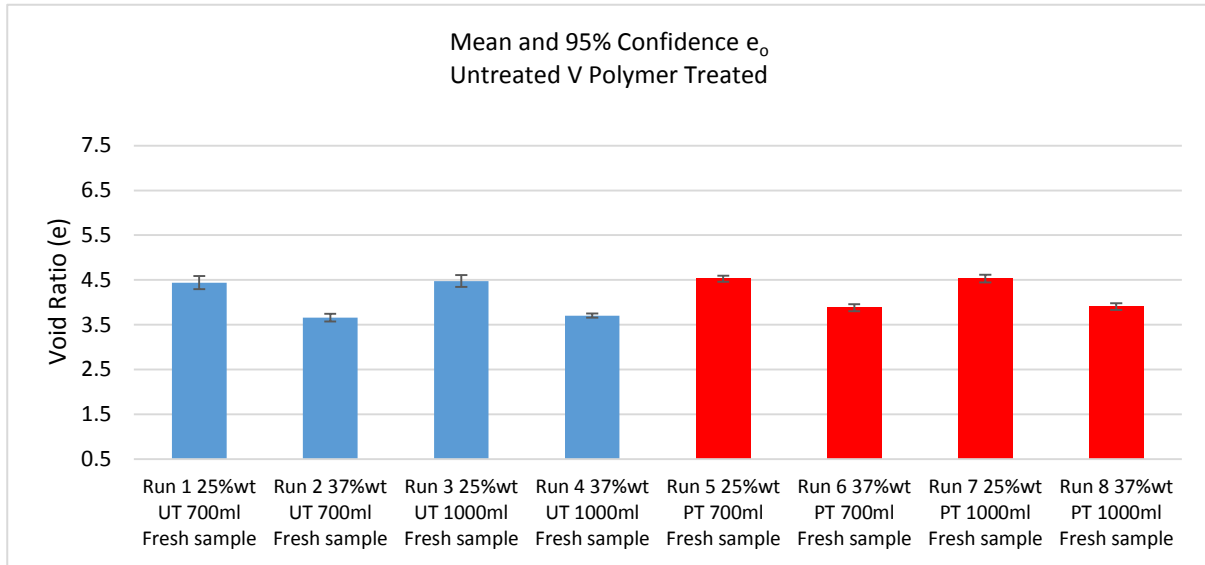
as a consolidation modelling input.

Figure 1 Beaker tests   determination PT versus UT

A comparison of fresh versus aged slurry was conducted to assess the validity of determining e_0, compressibility and permeability behaviour of tailings material that has been transported from its origin to a laboratory facility for testing and is no longer 'fresh'. Figure 2 illustrates that there is no significant variation in e_0 between the fresh and aged slurry for this substrate. Additionally, the data shows the same slight increase in e_0 for the PT high solids slurry that was seen previously in Figure 1.

It should be noted that e_0 determinations should only be directly compared for the same batch of synthetic slurry. The values of e_0 shown in Figure 2 are slightly higher than those shown in Figure 1 for the same conditions as they are different batches of slurry.
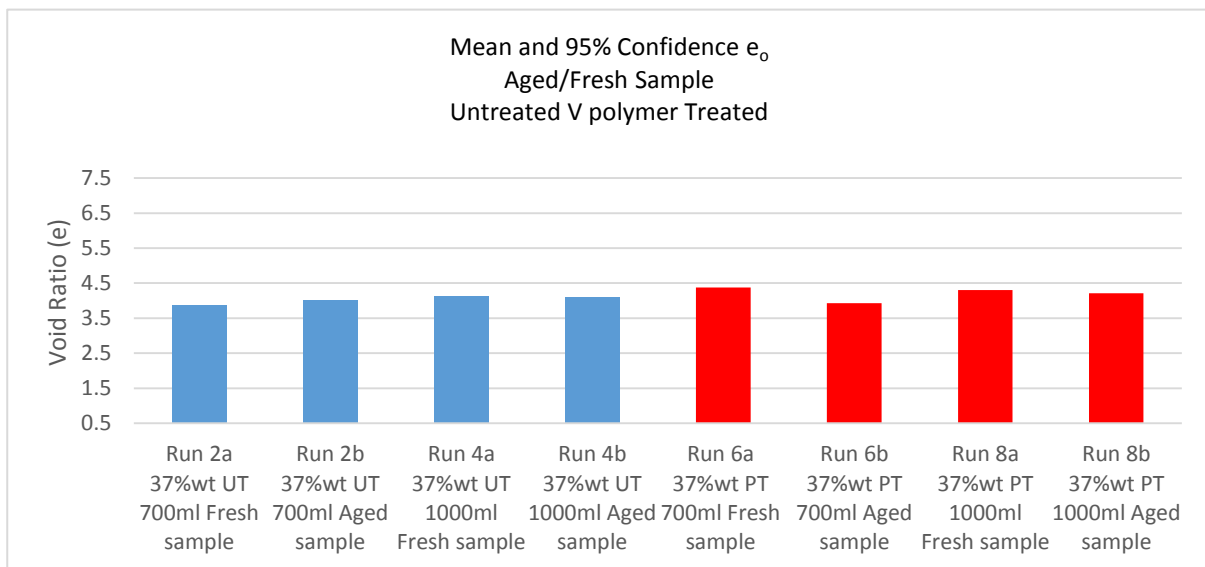

Figure 2 Beaker tests ageing impacts PT versus UT

3.2   Compressibility and permeability determinations

Figure 3 illustrates the variation of void ratio with vertical effective stress for PT and UT slurry, at high and low solids density, fresh and aged, measured using graduated cylinders.

The results of this study suggest no significant variation in void ratio with vertical effective stress through adjusting of initial slurry density for the UT slurry-i.e., the normal consolidation line (NCL) of the material

does not appear to have been affected. Previous testing and summaries on observed behaviour of slurries suggest that initial slurry solids content does not have a consistent effect on resulting NCL-in some cases an increased slurry density results in a denser (i.e., "lower" in void ratio space) NCL, while in some cases increased slurry density has no apparent effect (Reid and Fourie, 2015).

Compressibility data obtained using the 10 L columns, illustrated in Figure 4, suggests that there may be wall friction effects when estimating void ratio at varying effective stress for high solids slurries using a cylinder with an internal diameter (ID) of 62 mm versus the columns with an ID of 150 mm. The void ratios for the high solids slurry condition are consistently lower at comparable vertical effective stress when measured using the column as opposed to the cylinder.
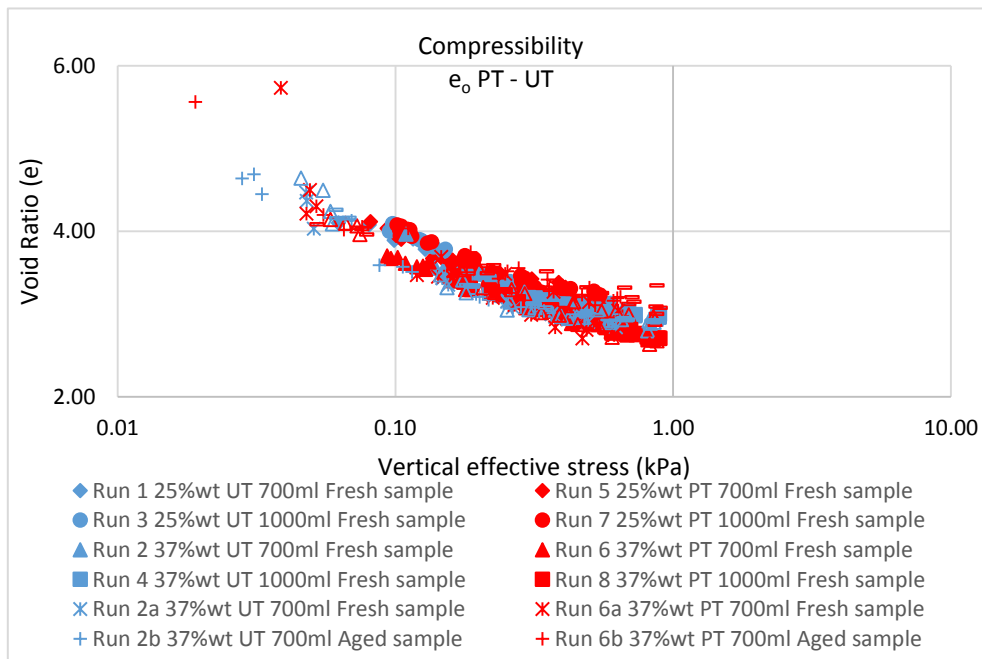

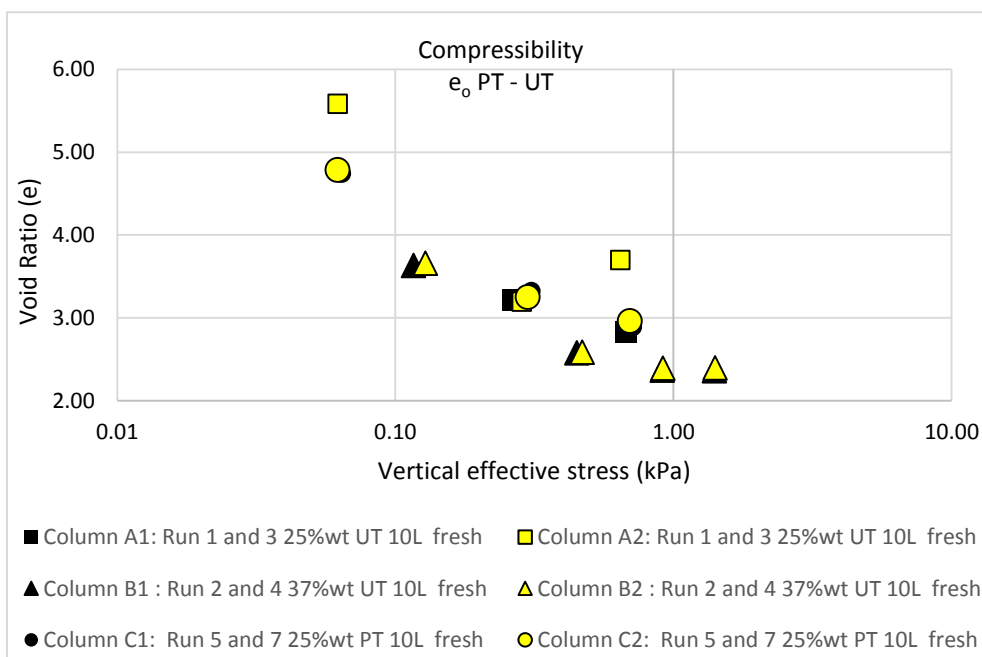**Figure 3   Void ratio at varying effective stress PT versus UT for the 1 L cylinders**

Figure 4   Void ratio at varying effective stress PT versus UT for the 10 L columns

In comparison to the UT samples, Figure 5 shows that PT tests indicated that varying the initial slurry density did result in an apparent variation to the resulting NCL. However, for PT, it is noted that varying the slurry

density required a variation in the polymer treatment procedure (331 g/t for low solids, 852 g/t for high solids).

Therefore, it is difficult to assess whether the apparent changes illustrated in Figure 5 were a result of the different slurry densities or variation in the polymer treatment procedures. In either case, it highlights the potential difficulties in reliable prediction of in situ densities to high accuracy levels, as even minor variations to deposited slurry density and resulting dosages can affect subsequent behaviour.
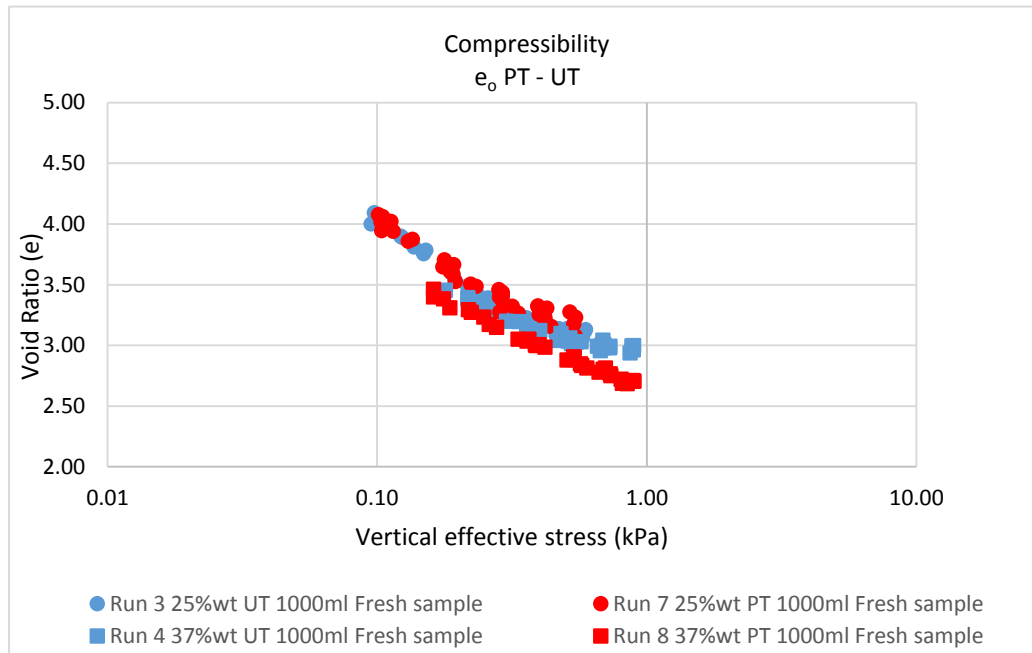

Figure 5   Void ratio at varying effective stress PT versus UT and 25wt% versus 37wt%

Figure 6 illustrates that the PT material gives consistently higher permeability at a given void ratio. This is a common observation for materials following polymer treatment. However, it is typical to only carry out a few such settlement tests. When many tests have been carried out, the results indicate a significant scatter, with each test type showing a range of one half to one order of magnitude comparing PT and UT.

Such variability would have significant impact on the results of a consolidation assessment for the material. It is noted that the high solids samples show generally greater scatter, likely owing to the smaller magnitude of settling for these samples and hence the reduced accuracy of settling distance measurements.

Figure 6 highlights the variability in void ratio between different batches of identical slurry. Three batches of slurry were used to generate the data in Figure 6;

Run 2a,b~ 8a,b

Column data A1,2~ C1,2

Run 1~8

Run 2a,b~8a,b have significantly different void ratios compared to the remainder of the data, likely caused by an increased polymer demand (1020 g/t for fresh and 1350 g/t for aged-all high solids condition) in comparison to Run 1-8 and the column data which had similar polymer treatment (331 g/t low solids and 850 g/t high solids).

The permeability data obtained using the 10 L columns overlays the data obtained using the graduated cylinders indicating that wall effects are not significant when estimating the permeability using the initial settlement rate.

Hydraulic conductivity clusters were obvious across all experimental runs, illustrated in Figure 6 with PT

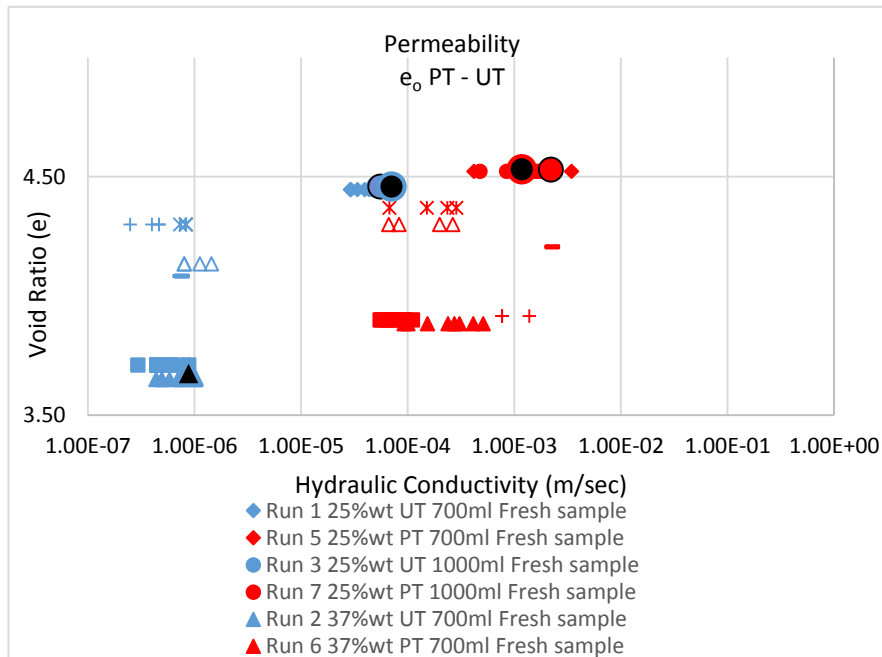typically showing an increase of 1~2 orders of magnitude when compared with UT material.

Figure 6   Hydraulic Conductivity PT versus UT

3.3   Large strain consolidation testing

A 37wt% solids sample was taken forward for larger strain consolidation testing than could be generated in the beakers. Illustrated in Figure 7, fitting a power trendline to each of the compressibility functions with an acceptable R2 value of (> 0.99 for PT, > 0.97 for UT sample), it is clear that a gap exists between the end of static dewatering, σ' = 1 kPa and where the consolidation tests begin, σ' = 10 kPa. Where permeability is concerned, illustrated in Figure 8, uncertainty between σ'=1 kPa and σ' = 10 kPa is more obvious.
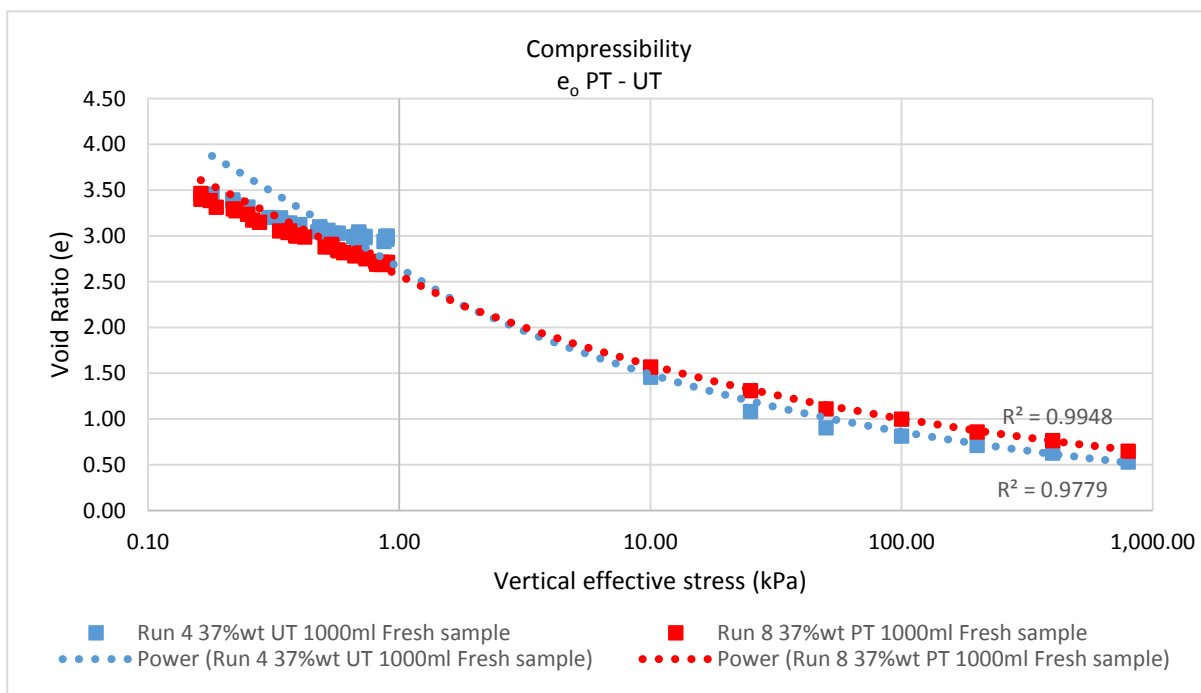

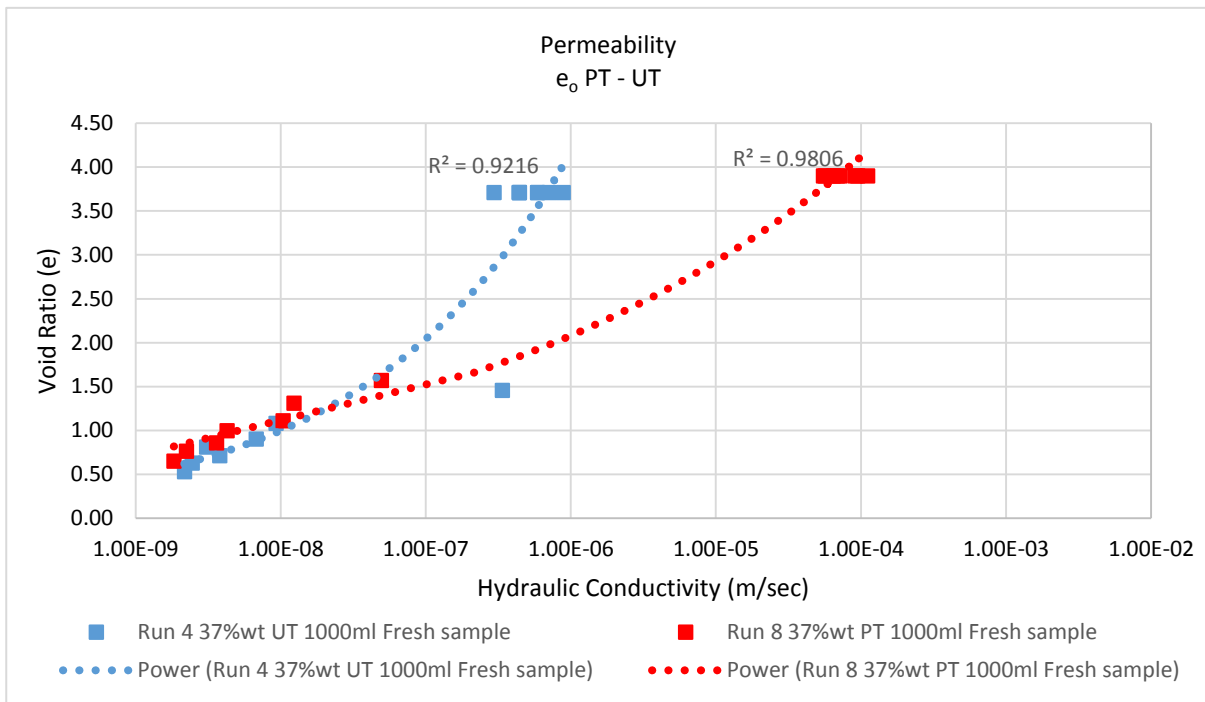**Figure 7   Beaker and rowe cell compressibility**

Figure 8   Beaker and rowe cell permeability

4   Conclusions

Uncertainty ranges in estimated values of e_0 have been determined using synthetic tailings material. 95% confidence intervals range from 0.047~0.14 for e_0 values in the range of 3.5~4.5 for a sample set of 8, highlighting the robustness of the described method and the viability of using experimentally determined e_0 as an input for consolidation modelling.

Sample ageing was found to have an impact on compressibility and permeability behaviour. However, it is likely that the variability relates to an increased polymer demand of aged material as opposed to variation of the consolidation behaviour of the material itself. The same is true for variations in void ratio observed at different solids densities as higher density slurries demand an increased polymer dosage.

Observations made using varying slurry height suggest that this factor has no impact on the measured e_0 void ratio. However, increasing the internal diameter of the vessels used to measure the void ratio at varying effective stress suggests that wall effects may be a factor at high solids densities.

Without information (e v k and e v σ') on material performance between where effective stresses start to generate, e_0, through to effective stresses past 10 kPa, it is not possible to generate data suitable for use in predictive models.

This work is consistent with common understanding that PT produces a more open fabric with higher permeability when compared with UT material. In some limited cases, PT produces a higher permeability at a lower void ratio, where aged samples were concerned.

5   Future work

Future work will continue to focus on methods that can be employed to predict field scale performance of PT v UT material. SICT results will be compared against Column and Rowe cell data to gain further insight into material response where PT is concerned. Further field scale trials are planned with various materials in order to gain further insight into lab estimations and field performance.

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